Needle shape quality control by shadowgraphic image processing

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ABSTRACT

In this paper, we propose a needle shape quality control method. For this end, we have devised a new acquisition system that combines a camera and a backlight. Needle measurements are carried out at a micrometric scale using shadowgraphic image processing. Our method not only distinguishes good needles from the bad ones, but also allows classifying flawed needles into various categories of defects. This classification is important as some categories of defects can affect the entire production while others do not. The results of our needle shape quality control method have been validated using real samples directly off the manufacturing line. Needles have been correctly classified at more than 97 % and accurate measurements on global shape characteristics such as straightness and sharpness have been obtained.

Keywords: metrology, quality control, image processing, needle

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1. INTRODUCTION

Nowadays, the inspection on production line of surgical needle shape and sharpness is done by human visual control, or simple physical tests such as scratching a surface or piercing a known material with the needle. These methods do not allow a precise measurement of the product quality to validate the manufacturing process. Needles are created from thin rod of alloys. Also, physical and chemical treatments are applied in order to obtain a reinforced structure and a sharp tip. Firstly, needles are quenched in order to obtain a stronger material. Then, a shot-blasting step allows us to eliminate deposits and to have a clean surface. A polishing stage gives needles their final form. Then, needles are put in a chemical bath to sharpen them. A varnish can be applied to protect needles from corrosion.

All these steps are necessary for needle manufacturing, but each step parameter has to be setup according to the result of the previous step. Indeed, the manufacturing step time depends on the alloy quality. For example, according to the result of the shot-blasting step, the polishing is more or less longer. It is hard to predict influences of each step, so the product quality can vary.

Currently, there is no system to accurately evaluate needle characteristics, it is, therefore, impossible to know whether a process step leads to a correct product or not. The manufacturing process moves on to the next step regardless of the previous step result. Our goal is to propose a method to identify defects and give access to specific measures to characterize each needle on production. Thus, each production step would be correctly parameterized.

Image processing [1] plays a key role in the quality control of numerous manufactured products. Recent advances in this field make it possible to extract, from images, some important features such as shape, color and other measurements. In this paper, we propose a needle shape quality control method that also classifies flawed needles into various categories of defects. This classification is important as some categories of defects can affect the entire production while others do not. In our method, needle measurements are carried out at a micrometric scale using shadowgraphic [2] image processing. Due to the limited depth of field of the camera, we chose to analyze the projected shadow of the needle using a backlight [3]. The shadow analysis gives good shape estimation with image processing. The combination of the camera's zoom and the shadow's magnification leads to a precision of one pixel for approximately 0.476 µm. The inspection area is 3272 x 2469 pixels i.e., about 1.175 mm x 1.558 mm.

A needle needs to have a conical body with a rounded tip. The body shape is evaluated by comparing the needle shadow with an ideal cone. We use the Radon transform [4] to find the lines supported by the needle's edges. However, due to irregular shape characteristics, we improve the shape determination by using morphological operators [5, 6] to estimate the ideal cone.

The needle tip is controlled by estimating its radius to assess its sharpness and its regularity. We use a morphological skeleton [7, 8] of the needle shape to obtain a Y-shaped structure and to estimate the needle tip roundness

Our paper is organized as follows. In Section 2, we present our method to precisely estimate the shape characteristics of the needle. Sharpness is analyzed in Section 3. Experimental results are presented in Section 4. Section 5 concludes our work.

2. SHAPE ANALYSIS

Our goal is to determine whether or not needle shapes are correct and to identify and quantify the manufacturing defects. These defects need to be translated into measurable characteristics. In order to classify needles, the study of the needle outline is sufficient. We propose to use a backlight to acquire the needle shadow (i.e., the needle is placed between the illumination source and the acquisition device). The resulting image can be reduced to a binary one using a threshold to distinguish the needle shadow from the background. The needle outline can be extracted with a Canny edge detector [9]. In order to obtain the needle shadowgraph [2], we use a profile projector [3, 10] combined with a CCD camera. The profile projector magnifies the needle tip thus enhancing the measurement accuracy.

This section is organized as follows. Needle characteristics and defects are described in section 2.1. Section 2.2 deals with geometric considerations about needles. Classification criterions are proposed based on the needle shape in section 2.3 and its convex hull in section 2.4.

2.1 Needle characteristics

Before establishing any control method, we must define the characteristics of a correct needle. There are many different needle lengths and diameters. The needle structure can be separated into two parts: the needle body and its tip. The body can be considered as a truncated cone with a round-shaped tip.

It is possible to extract characteristics of a correct needle. The main shape characteristic requirements are:

- straightness
- angularity
- sharpness

There are four main defects on a needle (Fig. 1) that are:

- A wrecked tip
- A crushed tip
- A bent tip
- A dull tip

Wrecked and crushed tips are often due to shocks during needles manipulation. They only affect some needles as they are punctual defect. Elongated and dull tips are the result of bad chemical sharpening and could affect the entire production.

2.2 Geometric considerations

To ensure that a needle is sufficiently sharp and resistant, the tip must be large at its base and must progressively get thinner. A correct needle has a conical body with a round-shaped tip. We use two different ideal cones to analyze the shape of the body and the tip. Thus, we define a cone with an angle α to describe the needle body and a cone with an angle β to describe the needle tip (with $\beta \geq \alpha$). These two parameters allow us to determine if the global shape is correct.

To evaluate the straightness of a needle, we use the main axis direction of the previously determined cones. We note γ the angle between the body cone axis and the tip cone axis. This measure allows us to determine the straightness of the observed needle.

The first step is to determine the ideal cone of the needle body. First, we have to find the lines that best represent the needle contours. Then, we use the Radon transform [4] to find a set of prominent lines in the picture [11] and to determine the body cone. The Radon transform highlights the possible lines in an image using an accumulator in polar coordinates [12]. Each contour pixel brings its contribution in the accumulator for all possible lines that can pass through it (according to the angle sampling). If a line contains *n* pixels, the contribution for this line in the accumulator will be *n*. This way, the problem of identifying the main lines in the image is reduced to global maxima localization.

Some manufacturing steps, such as the chemical sharpening, give a coarse surface and lead to an irregular contour. In this case, the contribution of contour pixels is biased. Some lines obtained with the Radon transform are not representative of the needle contour due to scattered pixels. To limit this phenomenon, we developed a variant of the Radon transform that allows eliminating wrong lines. We propose a pre-processing step based on mathematical morphology operators. For each angle θ considered in the Radon transform, we compute the opening of the outline by a θ oriented *l*-length segment. The union of these processed images gives a resulting image with all segments:

$$I = \bigcup_{\theta_i} \left[\left(O - A_{\theta_i} \right) + A_{\theta_i} \right], \tag{1}$$

where I is the resulting image, O is the needle outline, A_{θ_i} is the θ_i oriented segment, $+$ and $-$ are Minkowski addition and subtraction.

The image is only composed of segments which length is at least *l+1* pixels. The Radon transform now gives an accumulator where maxima correspond to lines (Fig. 2). For our purpose, the angular discretization step of the accumulator is set to 1°. A more precise estimation can be obtained by decreasing the angular step or interpolating accumulator data. We assume that the best representative line is given by the accumulator maximum. Once the first representative line found, the neighborhood of the maximum is set to zero to remove then we look for the second line. This way, the needle cone and alpha are found. The cone extremity is computed to determine the tip neighborhood. Using the same method on the tip neighborhood, we can access to the tip cone and beta.

2.3 Cone based criterions

These three parameters (α, β and γ) inform us about the global needle shape. These data are insufficient to completely define the needle. A too short needle cannot be detected. A "filling" ratio, corresponding to the amount of material in the ideal cone, gives this information:

$$Filling = \frac{|A \cap \Gamma|}{|\Gamma|}, \tag{2}$$

In the same way, a bent needle partly lies outside the ideal cone. An "overflow" criterion, corresponding to the amount of material outside the ideal cone, translates this problem:

$$Overflow = \frac{|A \cap \overline{\Gamma}|}{|A|}, \tag{3}$$

where A is the needle shape, Γ is the ideal cone area and $\overline{\Gamma}$ is its complement.

This overflow can also be the result of an elongated tip. To identify the needle's defect, a comparison between the cone length (L_c) and the needle length (L_n) is carried out. An elongated needle has a ratio L_c/L_n greater than 1.

2.4 Convex hull based criterions

A small bending on the tip is undetectable by the previous method. A correct needle is conic, therefore also convex. The convex hull [13, 14] is significantly modified by small modifications on the shape (Fig. 3). The Convex Outline Ratio (COR), which is the intersection between the needle outline and the dilated convex hull, provides information about the needle connexity:

$$COR = \frac{|C \cap (\xi \oplus T)|}{|C|}, \tag{4}$$

where $|\ |$ is the cardinality, C is the outline, ξ is the outline of the convex hull, $\oplus$ the dilation operator and T the dilation element. A 100% COR corresponds to a convex needle. The further COR gets from the perfect score, the more the shape of the needle turns concave. The dilation of the convex hull is usually limited to compensate the modification of the outline by discretization.

This measurement is completed by the computation of the area of intersection between the needle and the area covered by the convex hull. It refines the convex outline analysis as it provides an indication on the completeness of the convex hull; that is, the amount of material within its bounds. The Convex Area Ratio (CAR) provides such indication:

$$CAR = \frac{|A \cap \psi|}{|\psi|} \quad , \tag{5}$$

where $| \ |$ is the cardinality, A is the shape, ψ is the area covered by the convex hull. A 100% CAR occurs when the convex hull is full.

3. SHARPNESS ANALYSIS

Sharpness is one of the main needle characteristics. It translates the capacity of the needle to pierce a material. Our purpose is to precisely evaluate this property. In section 3.1, we propose an approach to link the sharpness to a physical measure. To get this measure, we present a method based on mathematical morphology in section 3.2.

3.1 Sharpness characterization

The measurement of the sharpness is not easy to evaluate. The first idea would be to follow the tip outline but it is too irregular to be successfully processed. As the tip mainly has a rounded shape, we have considered calculating the disk that best fills the tip. The smaller is the radius of the disk, the sharper the needle is. This method considers the global outline and avoids the curvature analysis. However, the calculation of the best fitting disk often turns out to be ambiguous as several disks can correctly fill the tip at different scales. Figure 4 shows two possible disks that correspond to this definition.

It is difficult to set a dimensional constraint on the disk as the size of the tip is needle dependant. Therefore, our approach is to take into account the geometry of the needle. More precisely, we based our method on physical tip aspects. We recall that the needle’s body is described as a truncated cone with a round-shaped tip. The connection between the body and the tip is characterized by a sudden change in the curvature of the contour. This change in the curvature is always present even when considering perfect real needles. It is due to the manufacturing process. One can observe two breakpoints arising at the junction between the tip and the body. These points depend on the needle shape and size. It is possible to develop an automatic method that makes use of these breakpoints. Due to the shape irregularity, these points are difficult to detect by following the contour.

3.2 Morphological approach

To avoid this problem, a regularization of the contour can be done but is dependant of the significance of the irregularity. Some breakpoints can be lost if this processing is too severe. It seems better to use a method which is not based on contour. Some operators of the mathematical morphology [5,6] are linked with the shape of objects. The skeleton transform [7] (also named medial axis) is one of these shape based operators. In two dimensions, it describes the locus of circle centers which have common points with the contour. The center of the best fitting disk lies on the skeleton of the needle. This transform can be significantly modified even by the slightest shape modification [8].

The skeleton of a cone consists of three segments. Each segment goes from a corner to an intersection with other segments (Fig. 5 left). The skeleton of a perfect needle is similar to the one of a cone. The only notable difference is on the top part of the skeleton (Fig. 5 middle). The skeleton of the rounded tip is reduced to a single point that coincides with the center of the best fitting disk. For a real needle, each breakpoint leads to a new segment in the skeleton. Each segment goes from the breakpoint itself to the center of the best fitting disk thus creating a Y-shaped structure (Fig. 5 right). In mathematical morphology, the Y-intersection is known as a multiple-point [5,6].

The roughness of the contour makes the skeleton irregular and numerous multiple-points can appear (Fig.6). Although a smoothing step can significantly reduced the number of multiple-points, some points can persist. This smoothing step is not essential to our method. Indeed, the sought multiple-point is found using a filling criterion. We consider each shape-limited incircle which center is a multiple-point. The filling criterion is the ratio between the upper half-circle area and the tip area beginning from the circle center to the tip extremity (Fig.7). The retained point is the one whose ratio is closest to one. In order to have relevant results, the needle geometry must be correct.

4. EXPERIMENTAL RESULTS

This study was led on an industrial partner production. The goal of this study was to classify needles in the same way as an expert and obtain cone angle and sharpness measures. In this section, we present a validation of our method on a large set of data in Section 4.1, 4.2 and 4.3 and a detailed analysis of a small representative sample set of several defects in Section 4.4. The method has given very satisfactory results both on measurements and classification.

4.1 Presentation of the database

The database is composed of 1500 needles. Each needle is taken at different stages of the production line after the polishing step. It is classified by two separate operators for a double-check classification. A post measurement in our partner laboratory gives us the tip sharpness and the needle angle (alpha) and tip angle (beta). These measures are considered as reference to compare our results.

The set is composed of:

- 450 perfect needles
- 250 bent body needles
- 250 bent tip needles
- 250 crushed needles
- 300 truncated needles

4.2 Measures

Table 1 shows the sharpness error and the angular precision in degree for alpha and beta cone and the deviation Gamma. The sharpness is not available for crushed and truncated needles as the tip is not round. The results are globally satisfying even if defects induce a precision decrease. The sharpness is correctly estimated comparing to the domain variation (10 to 35 µm) and the needed precision (± 5 µm) for the good needles. One can see that disturbances on the tip or its extremity logically increase the uncertainty of the measure. On the opposite, a measure on a truncated needle (no tip extremity) is the most precise.

4.3 Classification

The sample set is divided into five categories. In order to classify it, it is necessary to extract common properties and differences of each one. Table 2 shows the boundaries of each criterion to consider a needle as perfect. That is to say that needles that fulfill all these criteria would have a standard geometric shape. The values presented in Table 2 are set by heuristic. A specific database representing normal needles and presented defaults is used. Each category is then described by several samples and borderline cases in order to clearly define these heuristic values. Alpha, beta and gamma are product specifications.

The defects can also be identified:

1. Bent body: The needle is curved all along its length. Using our indicators, a deviation gives a high γ value. The shape is no longer convex so needle COR value is out of bounds. Material significantly overflows the α-ideal cone (see section 2). As the tip is not bent, tip's COR and overflow remains within admissible bounds (Table 3).
2. Bent tip: The needle body remains straight even if the needle end is crooked. γ value, tip's COR and overflow are not in the norm. We cannot predict needle's estimator values as it depends on the bent locus (Table 3).
3. Crushed needle: The tip was hit during manipulation and mashed. An excess of material can be found on each side of the tip. Material that remains on the side makes the tip's COR and overflow respectively low and high (Table 3). The needle must remain straight.
4. Truncated needle: This is a needle with no or an incomplete tip. At least, one of the filling criterions must be out of the norms (depending on alpha and beta values). The needle remains convex with no excess of material. As a result, COR and overflow have correct values.
5. Other defects: Some needle defects are singular and do not belong to a specific category.

Classification results are given in Table 4. Truncated needles are perfectly set in their category. Considering perfect needles, one can see that only three of them are not correctly evaluated i.e., 0.66 %. All the bent tips are detected as defects but some of the bent tip needles are set in the common defect category (3.2 %) i.e., the type of defect is not identified. This is not a problem while they are not set in other categories. Crushed needles are problematic as one is considered as perfect (0.4 %). In fact, the distortion of the tip is small (tip overflowing: 2.8 %) and do not modify its properties. Three crushed needles are placed into the bent tip categories. The distortion of the tip is located on one side, modifying the extremity geometry that become similar to a bent tip extremity. The defect of seven crushed needles is also not recognized (2.8 %). The worse classification is obtained for bent body needles. Only 92.8 % deals with the criterions and two needles are considered as perfect (0.8 %). Some needles are considered as bent tip needles as the curvature begins on the needle base and finishes on the tip (2 %). At last, eleven needles are only detected as flaws.

In conclusion, one can say that the distinction between good and flawed needles is efficient as only 6 over 1500 needles are incorrectly evaluated that is to say a rate over 99%. Defects are also correctly identified except the crushed and bent body ones which induce some false classification but the classification remains valid with a rate of 97% (40 incorrectly classified samples over 1500).

4.4 Detailed analysis

The experimental set consists of 20 images (Fig. 8) and represents the six categories previously defined.

The first goal of our experiment was to distinguish the good needles from the bad ones using the method described in this paper. As previously identified, only needles from 1 to 5 have a correct geometry. This is in agreement with the results we have obtained with our method and which are summarized in Tables 3, 4 and 5. Grey cells identify measurements that lay outside the bounds set for correct needles thus labeling the corresponding needle as bad. In the following, we use type I and type II errors, often referred to as “false positive” and “false negative”.

- “False positive” are needles falsely classified in a category.
- “False negative” are needles not classified in their correct category.

We also use:

- “True positive”: needles correctly classified in their category.
- “True negative”: needles rightfully rejected from a category.

Out of 20 needles, 19 were correctly classified and one was a “false negative” (Table 5). Considering the needle n°2, only the tip’s COR is outside the norm. This can be explained by the dirt on its tip that causes its convex hull to deviate from its outline. A defect on the shape is detected and the needle was considered bad. The defect does not correspond to a specific one so needle n°2 is assigned to “other defects” category. The needle classification by our method is relevant for good/bad distinction.

The second goal of this detailed analysis is to evaluate the classification of defects. The results are globally equivalent to the industrial classification. When focusing on false detections, only needles n°6, 17 and 19 are not in their correct category. Considering needle n°6, the defect is small. The tip is near a smooth correct one that is correlated to the sharpness measurement. The tip COR and the needle length ratio remain in the norm. Sample n°17 is described as a bent needle. Our method cannot classify it in the accurate group as its shape is almost straight. Pondering our results, we can describe it as a correct needle with an excess of material on the bottom right part of the body. The classification of needle n°19 is the most worrisome one since it is the only one whose defect is incorrectly identified as a known defect, precisely as a crushed needle. This needle is close to n°10 except that latter is not broken. In these two cases, the defect comes from a shock on the tip and can be considered as a crushed needle. Our classification, despite some differences with the industrial classification, is valid as variations can be completely and logically explained. We also can notice that the filling criterion and CAR are currently not used to classify. Their relevance would be more notable in the case of a lack of material (Fig.9) and useful for the classification of new defects. The sharpness results are suitable for correct needles as their typical sharpness are 15 µm (n°1, 4 and 5) and 30 µm (n°2 and 3). The method is not suitable for flawed needles as their geometry is incorrect. The sharpness precision is sufficient to decide if a needle is sharp or not.

5. CONCLUSION

In this study, we developed several methods to classify automatically the manufacturing of needles. Our results are rather good as corrected/flawed samples are identified at more than 99%. For any defect, the combination of all characteristics makes it possible to exclude needles that do not comply with industrial requirements. Needles that are within tolerances truly correspond to the expected good quality needles. The classification of defects is satisfactory (97%) despite some slight differences with the industrial one. Those variations can be explained and often lead to a different but valid classification. The measurement of the sharpness is correct for standard samples but can be uncertain for flawed ones.

The interest of the comparison of needles and ideal cones has been also demonstrated. The precision is adequate to the purpose and is significantly easier to use to microscopic device in industrial condition. Moreover, this method can be applied not only to classify end-products but also to obtain information on needles quality once polished to the end of production line. This allows to consider dynamic modifications of the process such as duration of chemical bath.

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7. BIOGRAPHIES

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YVON VOISIN received his Ph.D. degree in 1993 from the University of Franche-Comté, France. Since 2005, he has been a full professor at the University of Burgundy, France. He is also a member of the Image Processing group of the Laboratory Le2i ("Laboratoire d'Electronique, Informatique et Image"). His interests are the application of artificial vision, 3-D reconstruction and motion analysis.

Figure captions

- Fig. 1. Acquisition of projected needle shadows. From left to right: a correct, a crushed, a wrecked and a bent needle.
- Fig. 2. Original image (top). Orientation rectified image with α (white line) and β (dotted black line) (bottom).
- Fig. 3. A rectified image of a needle (top). A binarized needle (white) with its original (black) and dilated (grey) convex outline (bottom).
- Fig. 4. An example of two possible describing circles.
- Fig. 5. The skeleton of a cone (left), the skeleton of a perfect tip (middle) and the skeleton of a real tip (right).
- Fig. 6. Skeleton (left) and resulting fitting disk (right) on raw data.
- Fig. 7. Filling criterion: a good (left) and a bad (right) filling disk.
- Fig. 8. A set of needles as classified by an operator: correct needles (n°1 to 5), crushed needles (n°6 to 10), truncated needles (n°11 to 13), bent tips (n° 14 and 15), bent bodies (n°16 and 17) and other defects (n°18 to 20).
- Fig. 9. A binarized needle typically detected bad thanks to the filling criterion and CAR.
- Fig. 10. Photograph of Fabrice MAIRESSE.
- Fig. 11. Photograph of Tadeusz M. SLIWA.
- Fig. 12. Photograph of Michael ROY.
- Fig. 13. Photograph of Yvon VOISIN.

Table captions

- Table 1. Precision Table.
- Table 2. Correct geometry of a needle.
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- Table 4. Classification of the database.
- Table 5. Results of the detailed analysis.
- Table 6. Results of the detailed analysis.
- Table 7. Classification for the detailed analysis.

Mesure precision	Quantity	Alpha absolute error in degrees		Beta absolute error in degrees		Gamma absolute error in degrees		Sharpness absolute error in µm	
		mean	standard deviation	mean	standard deviation	mean	standard deviation	mean	standard deviation
Bent Body Tips	250	0.74	0.44	0.48	1.86	0.91	1.16	1.63	1.99
Bent Tips	250	0.34	0.23	0.66	1.76	0.41	1.19	0.84	1.3
Crushed Tips	250	0.35	0.37	0.73	1.43	0.37	0.69		
Perfect Tips	450	0.18	0.13	0.38	0.76	0.24	0.42	0.63	0.63
Truncated Tips	300	0.17	0.11	0.25	0.18	0.17	0.12		

Table 1. Precision table

Angles			
$\alpha < 30^\circ$	$\beta < 40^\circ$	$\gamma < 5^\circ$	
Needle			
Overflow < 5°	Filling > 0.85	COP > 0.80	CAP > 0.90
Tip			
Overflow < 5°	Filling > 0.80	COP > 0.80	CAP > 0.80

Table 2. Correct geometry of a needle.

Needle category	Alpha	Beta	Gamma	Needle				Tip			
				Overflow	Filling	COR	CAR	Overflow	Filling	COR	CAR
Crusched	▪	▪	✓	▪	▪	▪	▪	×	▪	×	▪
Bent body	▪	▪	×	×	▪	×	▪	✓	▪	✓	▪
Bent tip	▪	▪	×	▪	▪	▪	▪	×	▪	×	▪
Perfect	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
Troncated	▪	▪	▪	✓	(1)	✓	▪	✓	(1)	✓	▪

✓: in the norm, ×: not in the norm, ▪: not considered, (1) at least one must be not in the norm

Table 3. Requirements for classification of defects.

Category	Quantity	Automatic classification					
		Bentbody	Bent tip	Crushed	Perfect	Other defects	Truncated
Bent body	250	232 (92,8 %)	5 (2 %)	0	2 (0,8 %)	11 (4,4 %)	0
Bent tip	250	0	242 (96,8 %)	0	0	8 (3,2 %)	0
Crushed	250	0	3 (1,2 %)	239 (95,6 %)	1 (0,4 %)	7 (2,8 %)	0
Perfect	450	0	0	0	447 (99,33 %)	3 (0,67 %)	0
Truncated	300	0	0	0	0	0	300 (100 %)

Table 4. Classification of the database.

		Angle			Overflow		Filling	
N°	Category	Alpha	Beta	Gamma	Needle	Tip	Needle	Tip
1	Correct	13	21	1	0.35479	2.1553	93.804	83.1707
2		18	25	3.5	0.72946	4.9377	92.6891	86.5044
3		24	33	1.5	0.82488	1.0845	91.8974	87.2695
4		19	27	1	0.29228	0.88198	95.9359	84.5906
5		14	30	0	1.9413	0.8099	87.9343	88.2355
6	Crushed	26	22	0	1.2981	5.7975	88.5354	59.1391
7		14	28	62	4.9822	100	72.4485	0
8		10	79	52.5	0.93877	45.7002	72.7379	98.6352
9		10	78	29	6.2565	12.7733	69.5934	99.3607
10		22	38	85	12.7971	86.69	85.4691	97.1674
11	Truncated	16	41	0.5	0.41484	0.47954	75.3705	82.4636
12		11	26	5.5	0.55867	0.41843	80.0154	61.4976
13		10	29	3.5	3.2849	4.5588	82.9254	86.4502
14	Bent tip	24	12	34	2.8823	33.0191	95.2927	99.1801
15		24	33	35.5	11.9745	55.5663	96.5913	79.2485
16	Bent	10	23	20.5	7.5709	0.59029	68.1743	68.4816
17		12	18	3	11.2958	4.2182	87.4781	80.86
18	Others	24	23	1.5	1.2706	9.8614	98.6885	91.8513
19		12	13	2.5	15.4249	73.4151	82.4114	67.8437
20		8	29	2.5	2.4296	98.3403	60.8929	91.0555

Table 5. Results of the detailed analysis.

N°	Category	Tip Sharpness	CAR		COR	
			Needle	Tip	Needle	Tip
1	Correct needle	13.80	0.982	0.944	0.900	0.892
2		26.61	0.948	0.882	0.875	0.791
3		28.32	0.98443	0.955	0.885	0.879
4		16.16	0.978	0.963	0.977	0.918
5		14.26	0.969	0.979	0.931	0.913
6	Crushed needle	67.22	0.910	0.9019	0.726	0.881
7		1.43	0.912	0.920	0.777	0.532
8		35.53	0.942	0.883	0.871	0.502
9		48.99	0.879	0.959	0.728	0.737
10		46.65	0.868	0.986	0.583	0.781
11	Truncated needle	55.69	0.957	0.979	0.828	0.892
12		72.38	0.973	0.979	0.913	0.937
13		35.38	0.945	0.825	0.955	0.875
14	Bent tip	7.03	0.858	0.867	0.763	0.708
15		19.16	0.907	0.747	0.679	0.450
16	Bent body	41.04	0.908	0.976	0.762	0.899
17		23.34	0.882	0.939	0.818	0.937
18	Other defects	17.92	0.952	0.899	0.764	0.647
19		10.96	0.759	0.840	0.544	0.296
20		25.57	0.897	0.783	0.735	0.612

Table 6. Results of the detailed analysis.

Category	True Positive	True Negative	False Positive	False Negative
Correct needle	4	15	0	1
Bent body	1	18	0	1
Bent tip	2	18	0	0
Crushed needle	4	14	1	1
Truncated needle	3	17	0	0
Other defects	2	14	3	1

Table 7. Classification for the detailed analysis.